Can over-spinning Kerr geometry be the souce of ultra-high energy particles ?

(Based on arXiv:1510.08205.)

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Earth is bombarded with the ultra-high energy particles from outer space (ultra-high energy cosmic rays 10^{20} eV, ultra-high energy neutrinos 10^{15} eV).

The mechanism responsible for the generation of ultra-high energy particles remains an enigma and topic of active ongoing investigation.

All the known mechanisms make use of electromagnetic interaction.

We try to understand whether GRAVITY can be used to generate ultra-high energy particles.

We show that Penrose process in the over-spinning Kerr spacetime geometry can be used to energize particles to high energies.

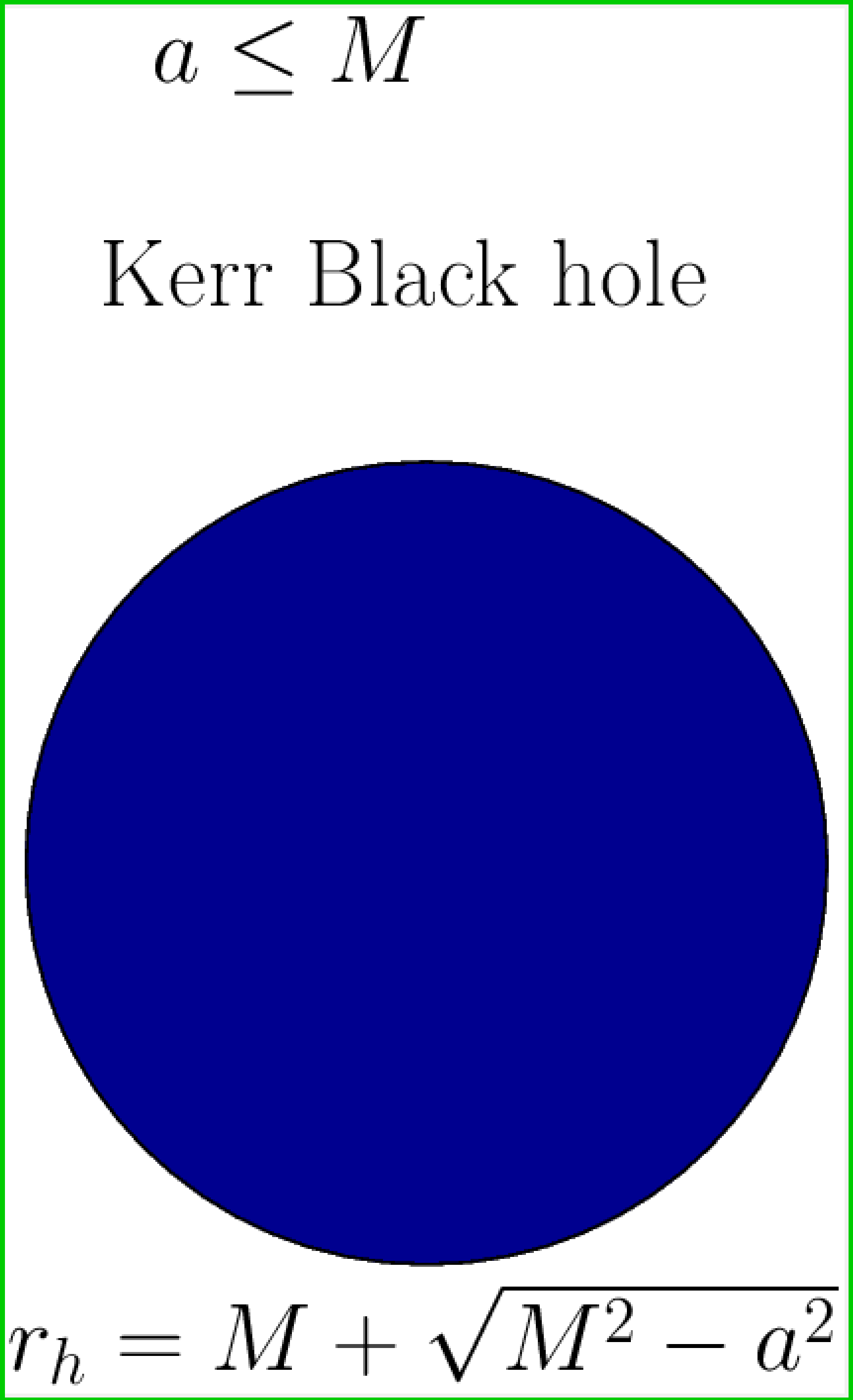
Kerr metric

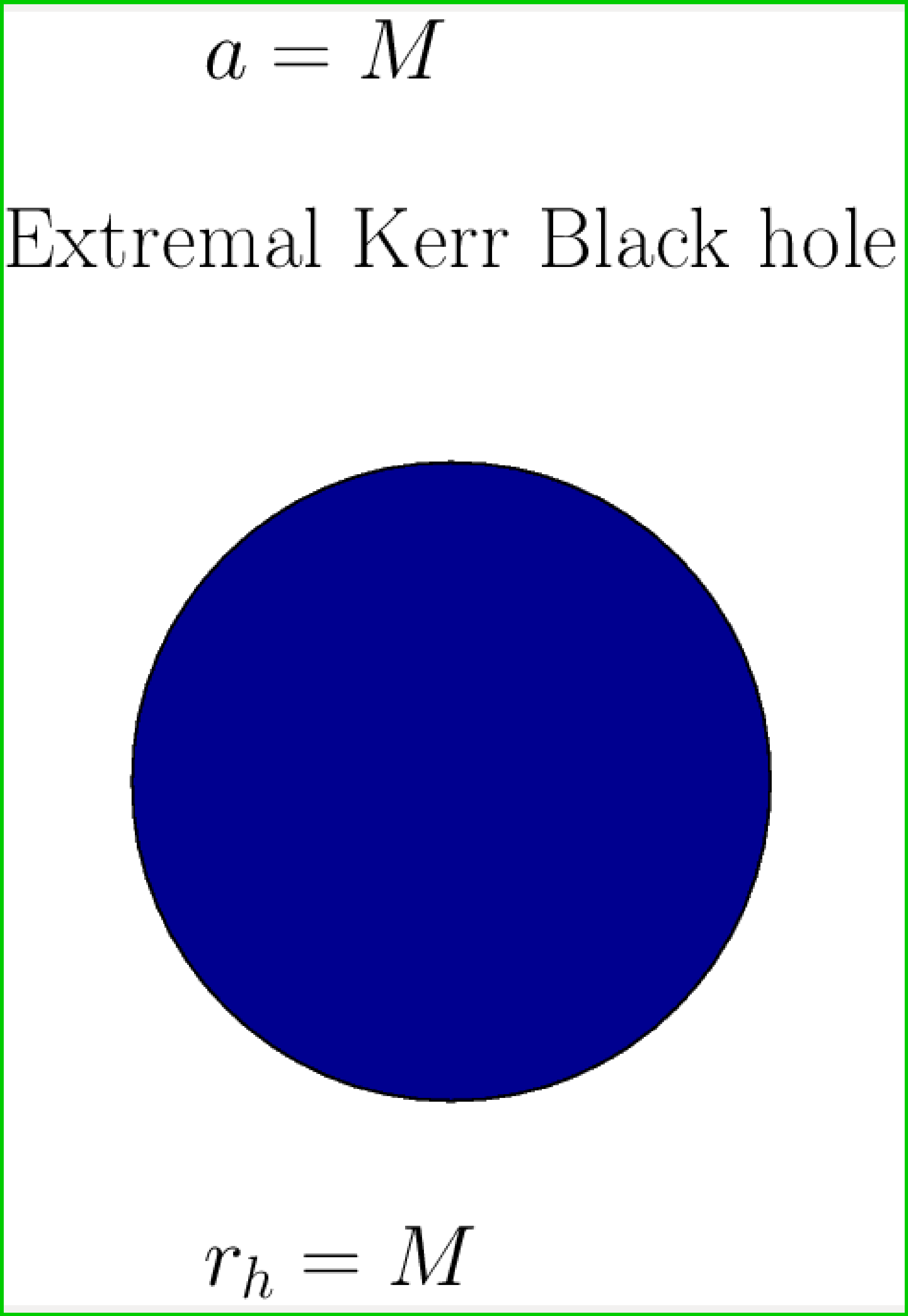
Kerr Metric written in the Boyer-Lindquist ccordinate system.

$$ds^2 = -\frac{\Sigma\Delta}{A}dt^2 + \frac{A}{\Sigma}\sin^2\theta\left(d\varphi - \frac{2aMr}{A}dt\right)^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2,$$

$$\begin{aligned}\Delta &= r^2 - 2Mr + a^2,\\ \Sigma &= r^2 + a^2\cos^2\theta,\\ A &= (r^2+a^2)^2 - a^2\Delta\sin^2\theta.\end{aligned}$$

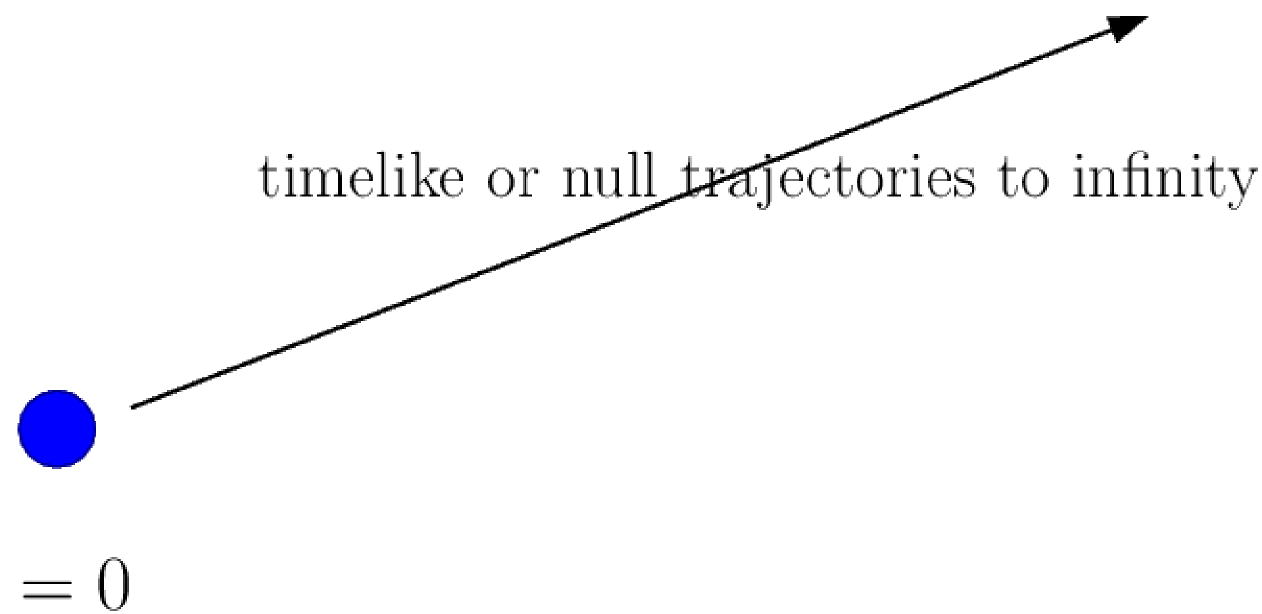
It contains two parameters. Mass '*M*', angular momentum or spin '*a*'


$a \leq M$
Kerr Black hole
$r_h = M + \sqrt{M^2 - a^2}$


$a = M$
Extremal Kerr Black hole
$r_h = M$

$a > M$

Over-spinning Kerr geometry



Kerr Naked Singularity

$$ds^2 = -\frac{\Sigma\Delta}{A}dt^2 + \frac{A}{\Sigma}\sin^2\theta\left(d\varphi - \frac{2aMr}{A}dt\right)^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2,$$

$$\begin{aligned} \Delta &= r^2 - 2Mr + a^2, \\ \Sigma &= r^2 + a^2\cos^2\theta, \\ A &= (r^2 + a^2)^2 - a^2\Delta\sin^2\theta. \end{aligned}$$

Kerr metric is independent of ‘*t*’ and ‘*φ*’.

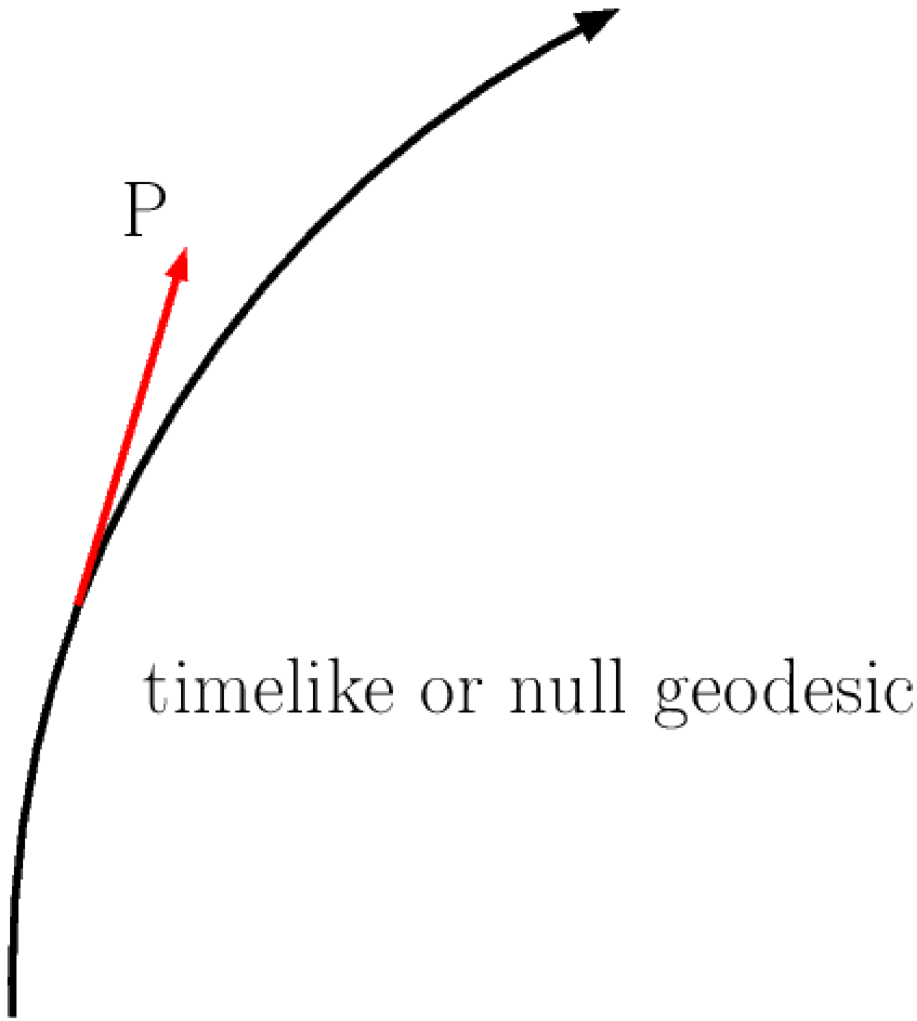
It admits symmetries $t \rightarrow t + c$, $\varphi \rightarrow \varphi + c$.

Kerr metric admits Killing vectors ∂_t and ∂_φ .

Constants of motion

$$E = -P \cdot \partial_t$$

$$L = P \cdot \partial_\phi$$



E = Conserved energy.

L = Conserved angular momentum.

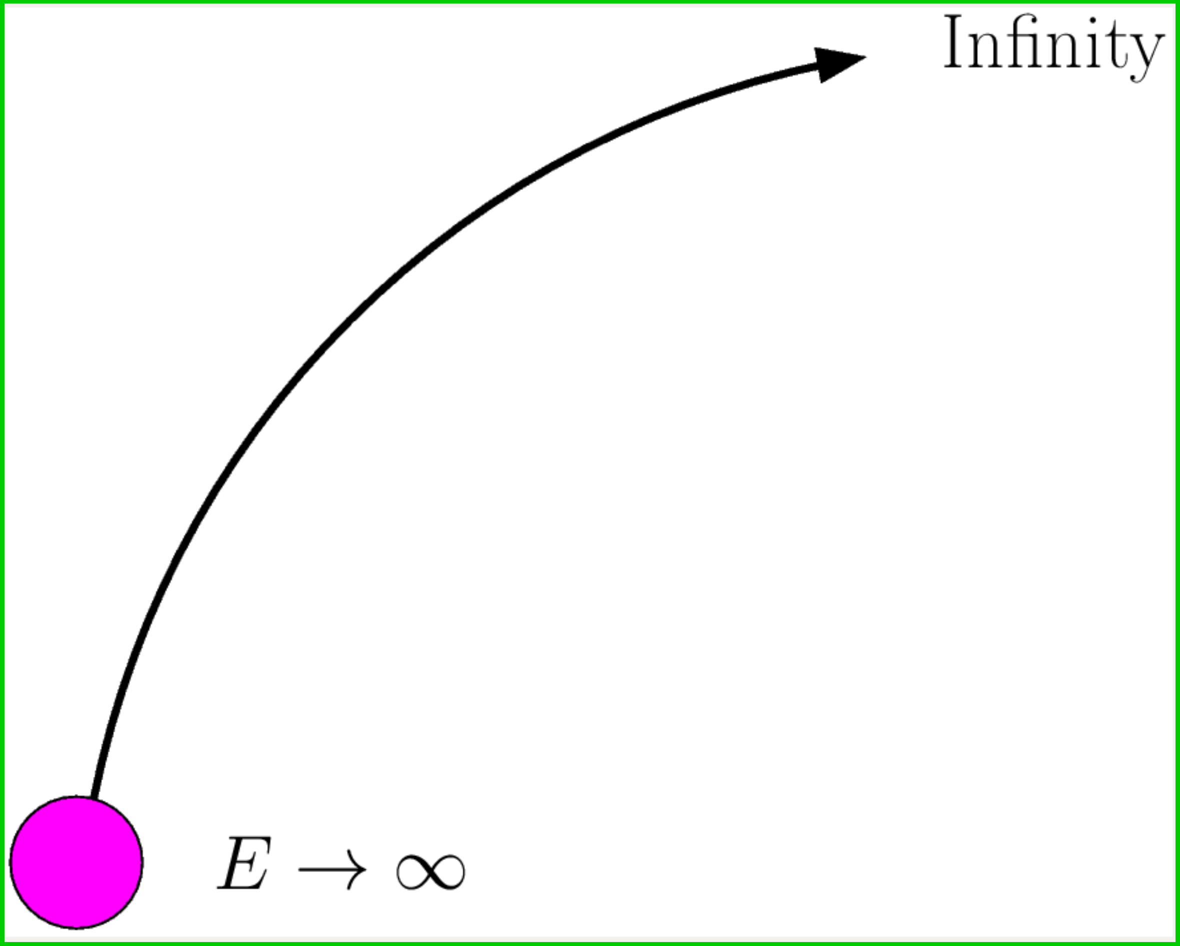
E is the energy as measured by the observer at infinity.

L is the angular momentum as measured by the observer at infinity.

In order to generate ultra-high energy particle...

1. Produce a particle with large conserved energy E in the Kerr spacetime.

2. Make sure that the particle escapes to infinity.



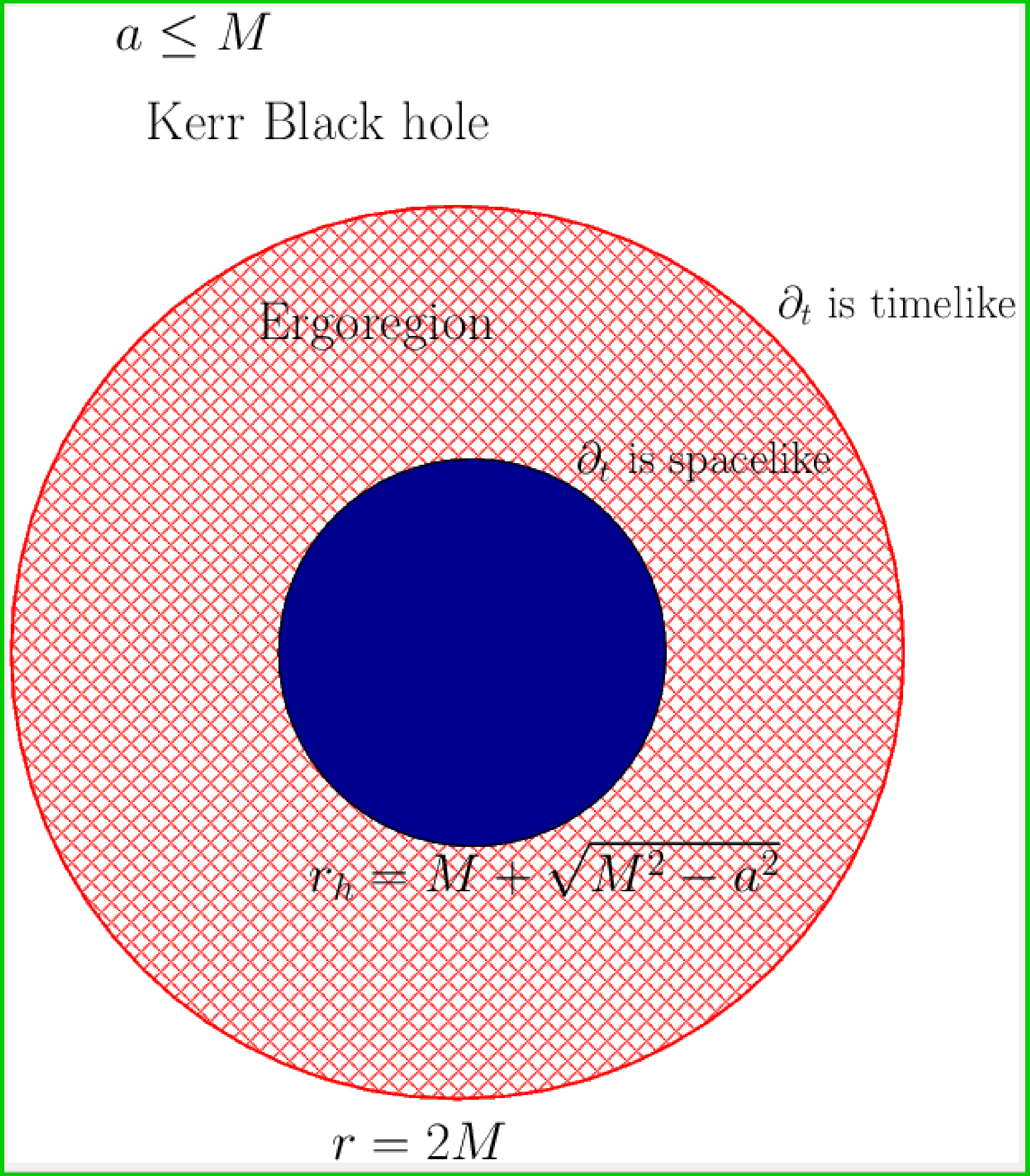
Penrose Process

Norm of the Killing vector ∂_t : $N=\partial_t . \partial_t=-(1-2M/r)$

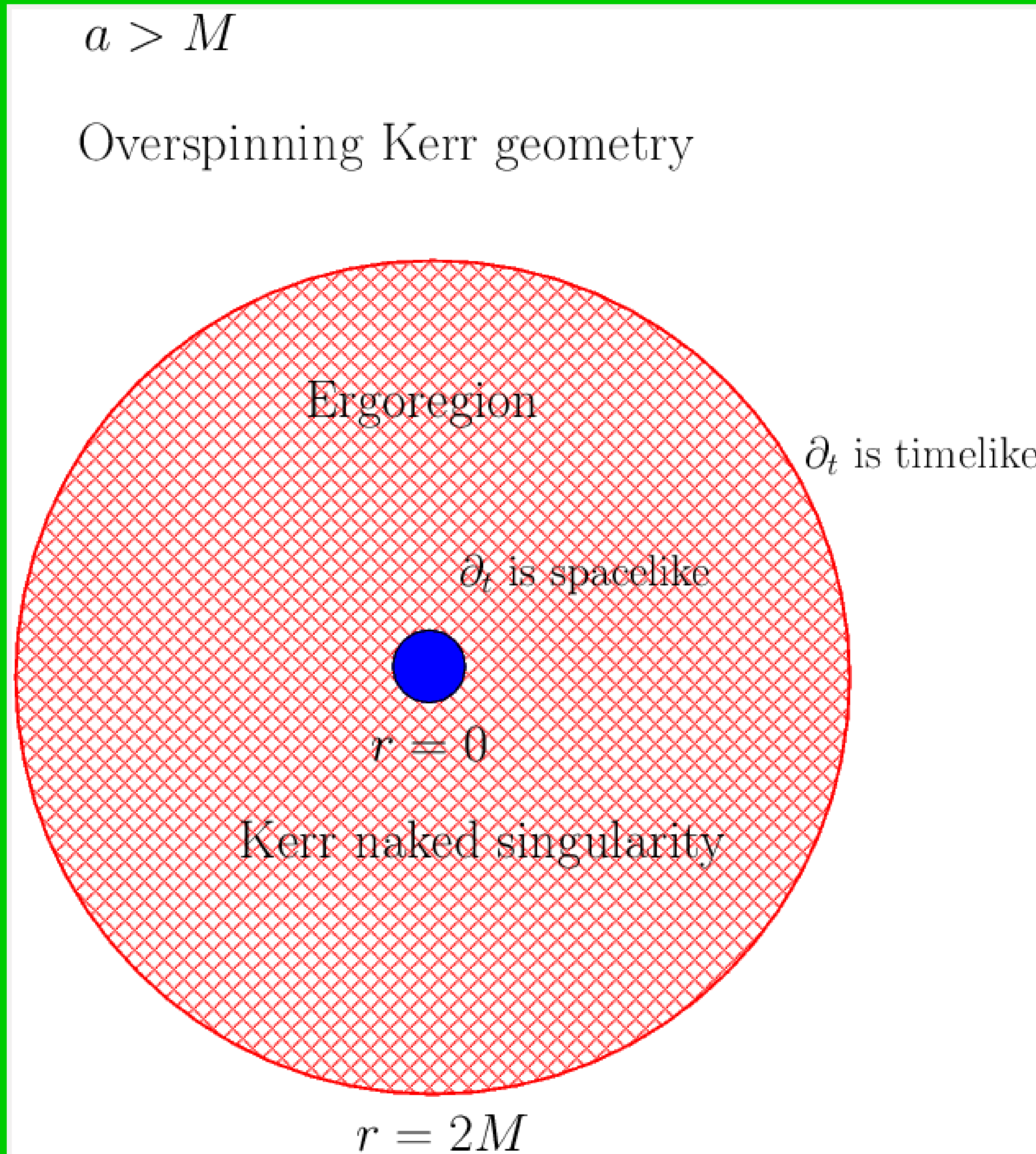
When $r>2M$, $N<0$, ∂_t is a timelike vector.

When $r<2M$, $N>0$, ∂_t is a spacelike vector.

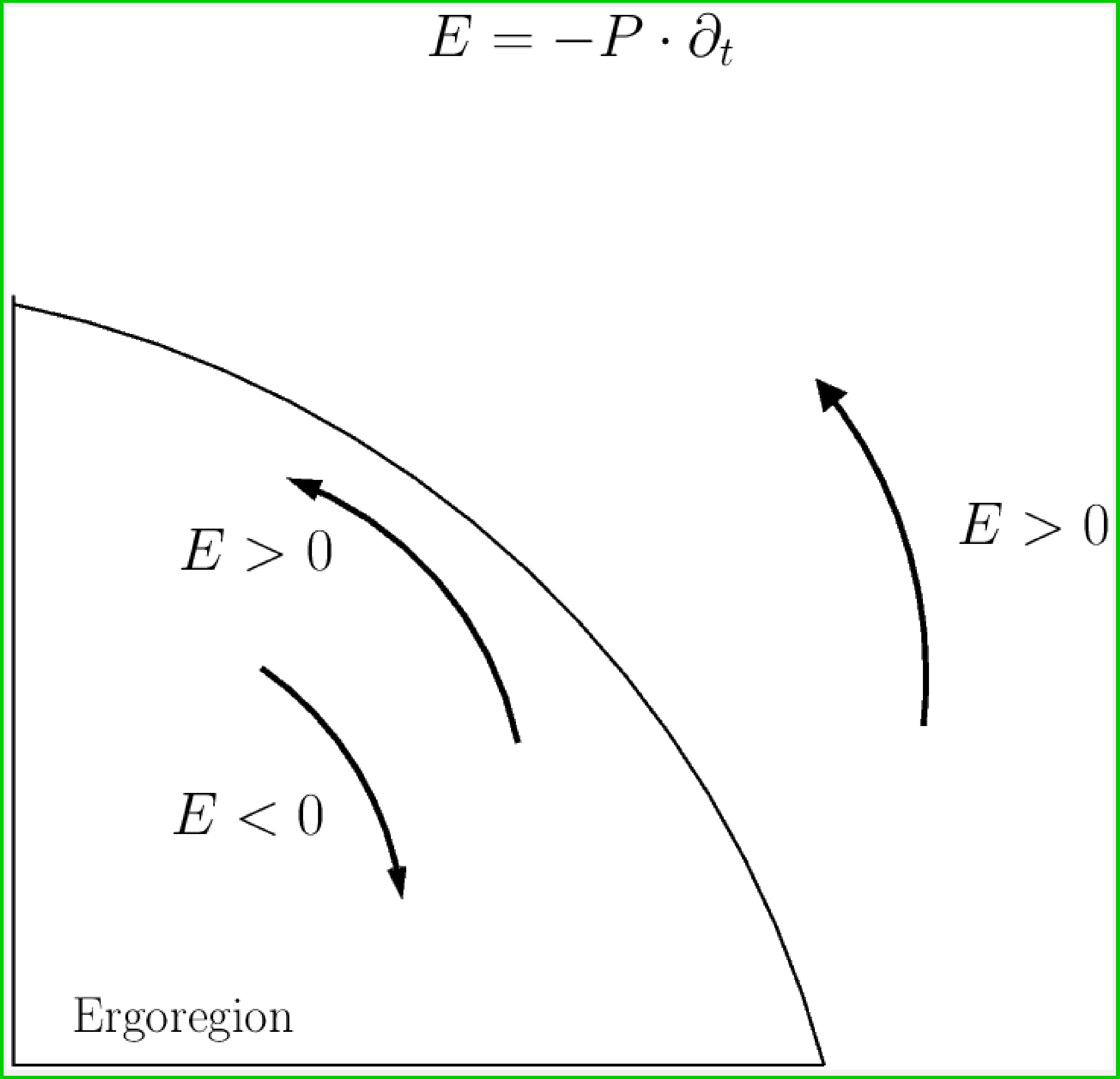
Region where ∂_t is a spacelike is known as Ergoregion.



Ergoregion extends from black hole event horizon to r=2M.

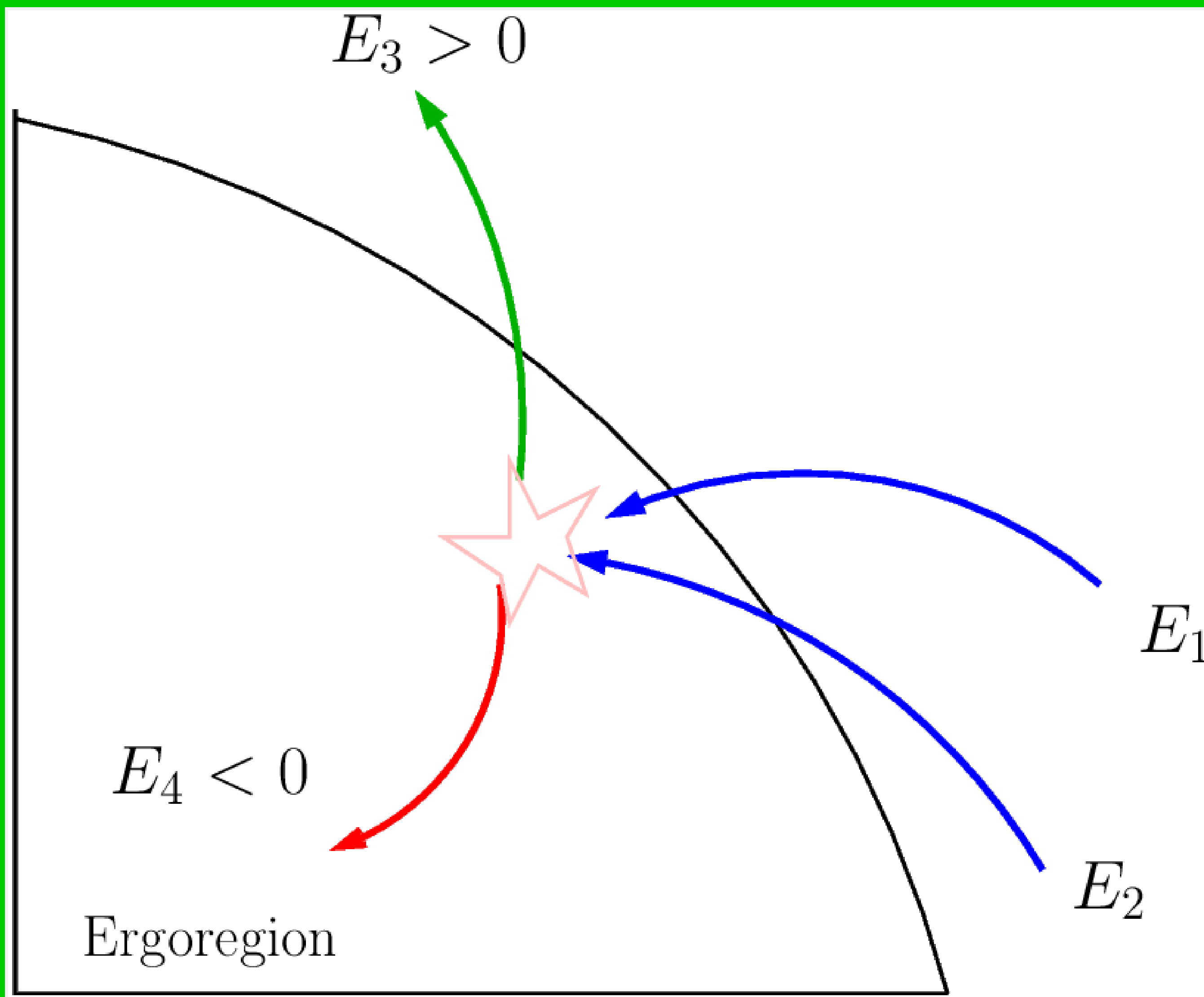


Ergoregion extends from singularity to r=2M.



Geodesics with negative conserved energy can exist inside ergoregion.

Penrose Process

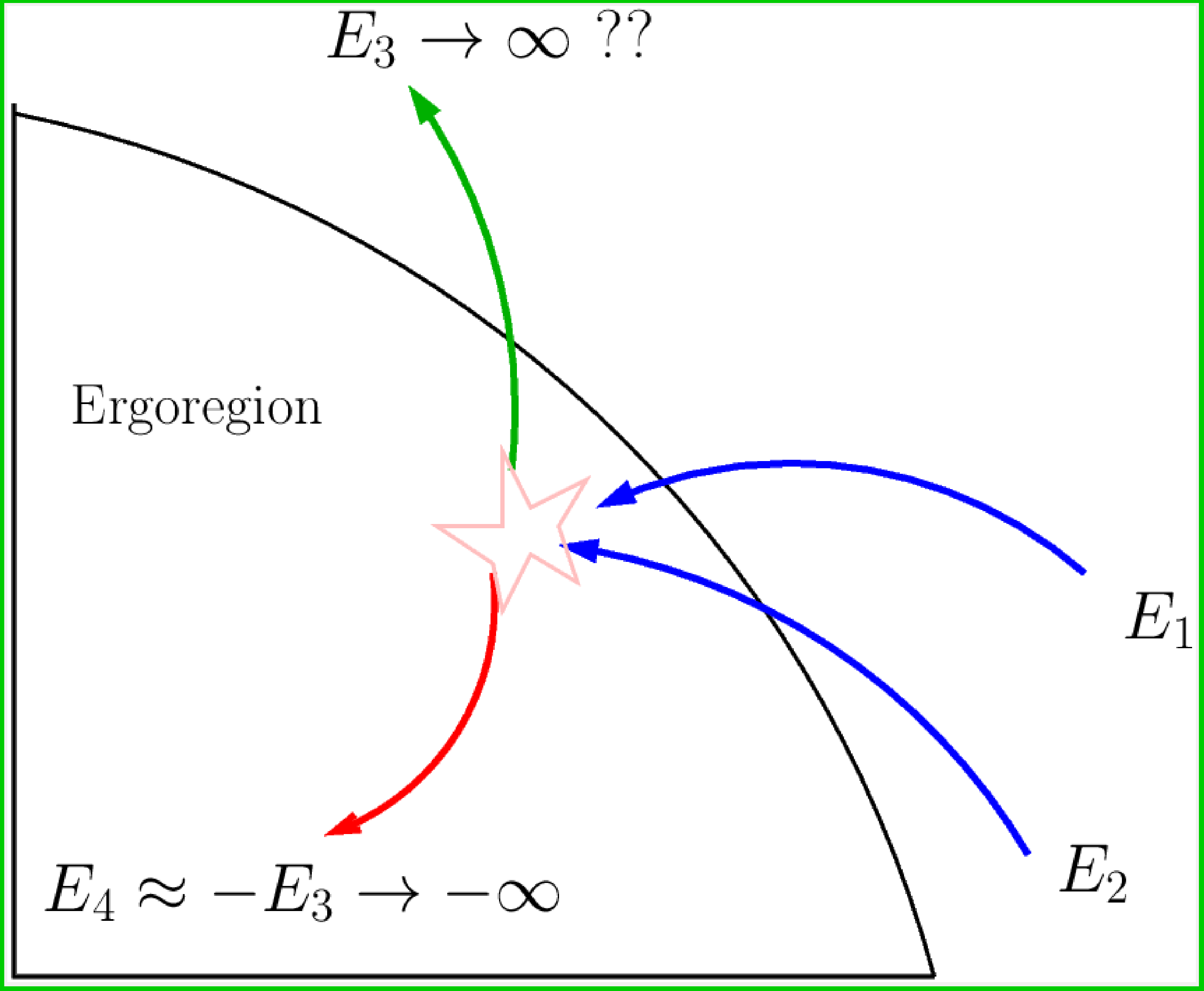


$E_4 < 0$

$E_3 = (E_1 + E_2) - E_4$
$> (E_1 + E_2)$

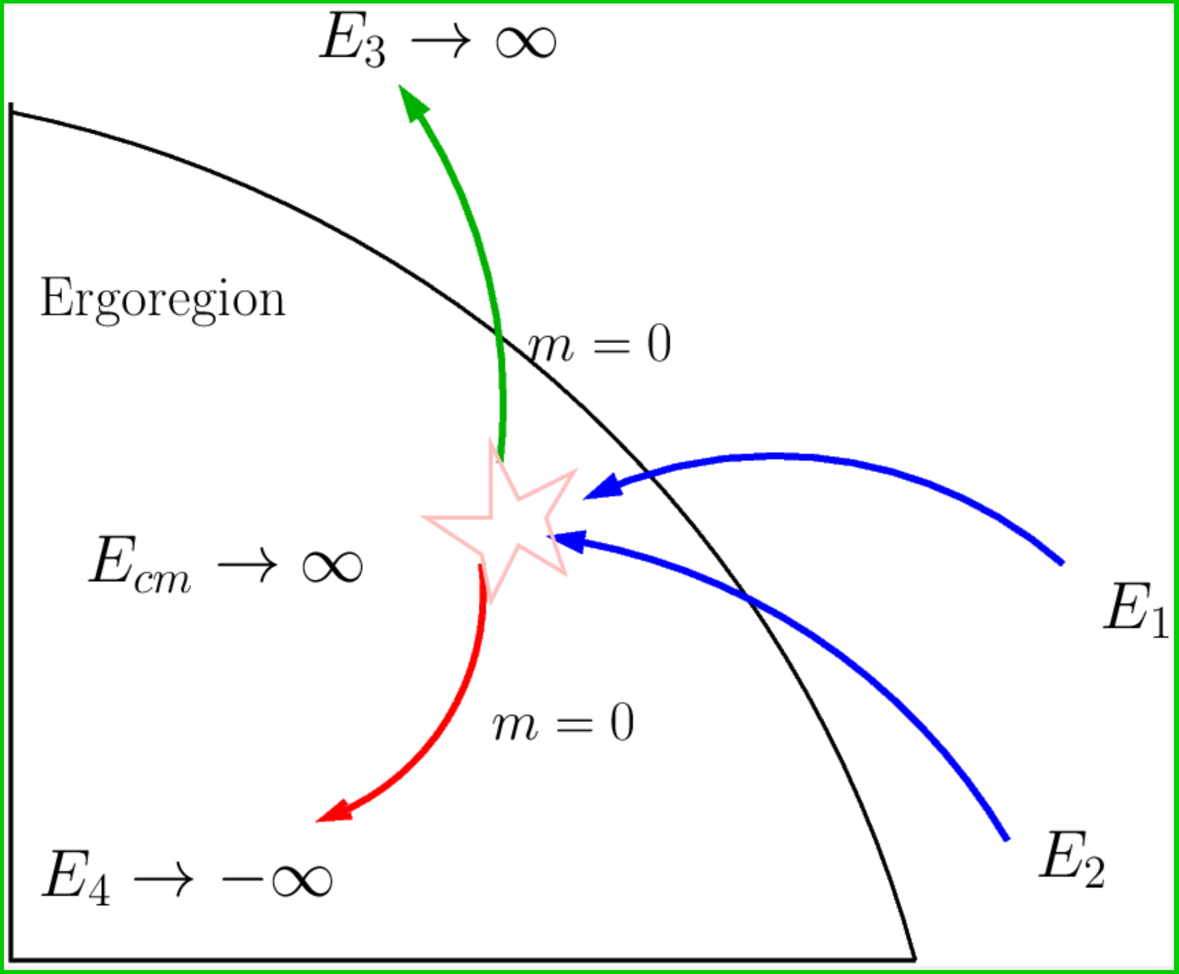
Energize particles by extracting energy from Kerr geometry.

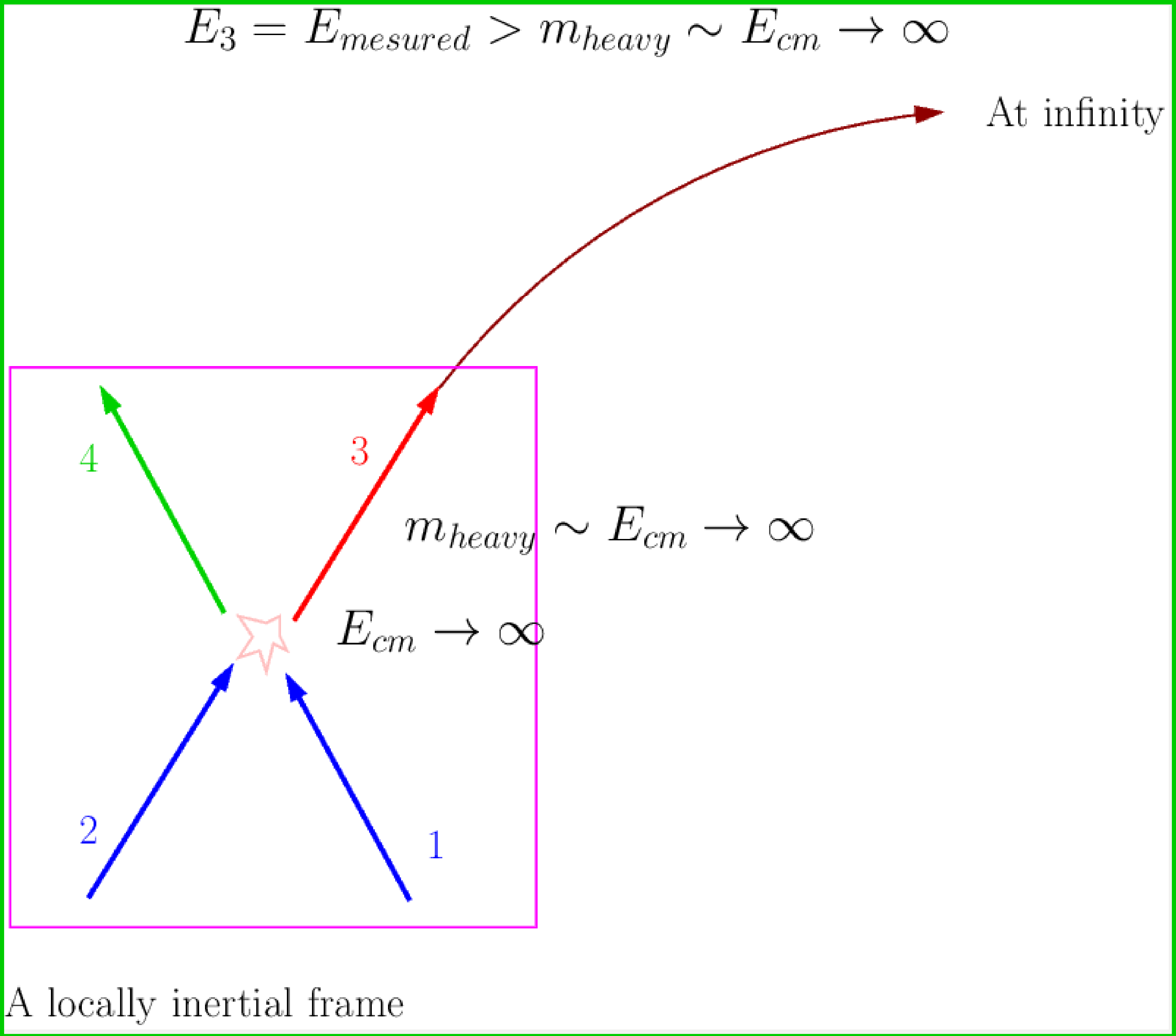
Can Penrose process generate particle with large conserved energy ?



We consider a process where two massive particles collide inside the ergoregion of Kerr spacetime and produce two massless particles.

We show that the necessary and sufficient condition for the production of particle with large conserved energy is the divergence of the center of mass energy of collision.




$E_3 = E_{mesured} > m_{heavy} \sim E_{cm} \to \infty$
At infinity
4
3
$m_{heavy} \sim E_{cm} \to \infty$
$E_{cm} \to \infty$
2
1
A locally inertial frame

Can center of mass energy of collision diverge in Kerr spacetime?

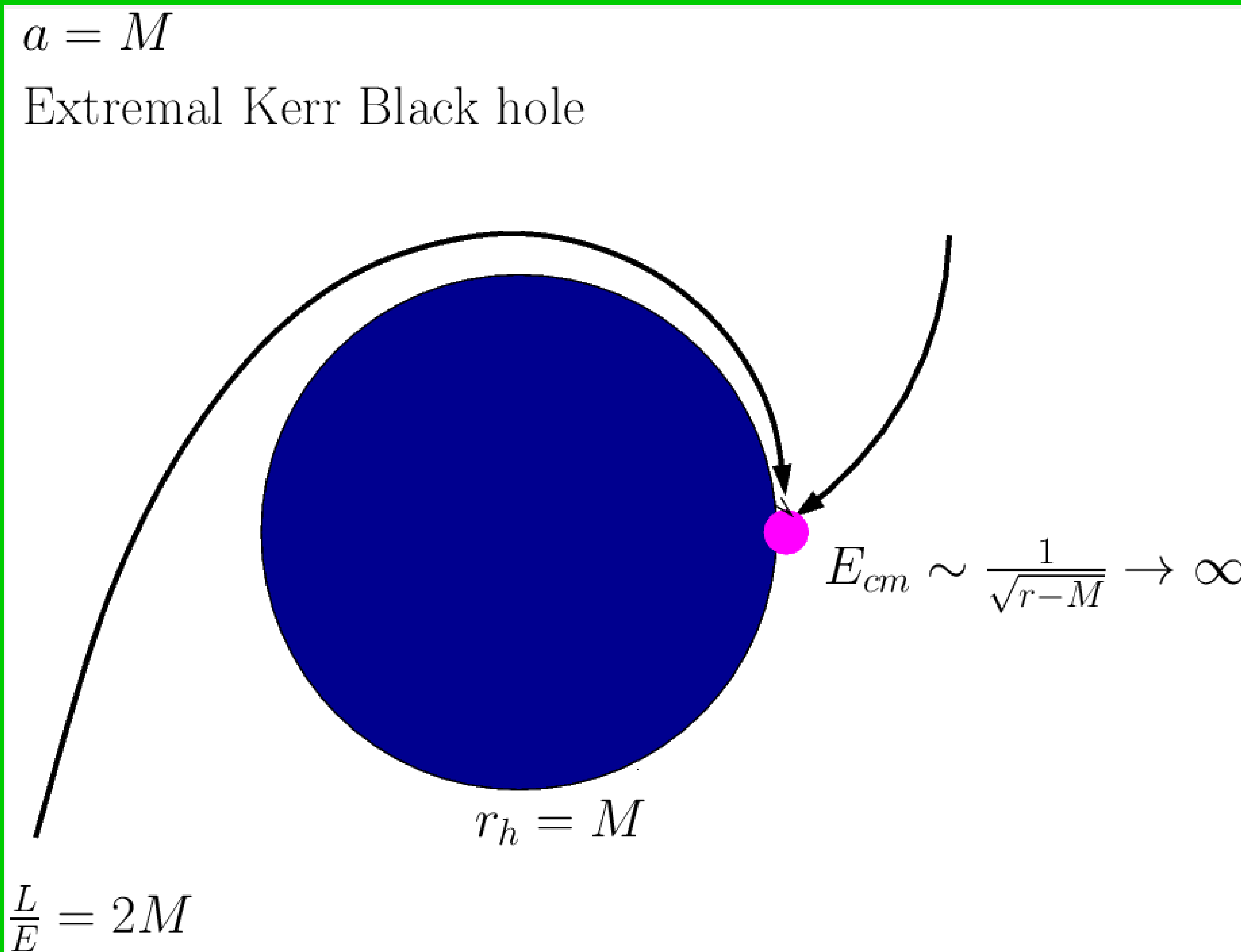
Extremal Kerr black hole

Banados, Silk, West PRL 09

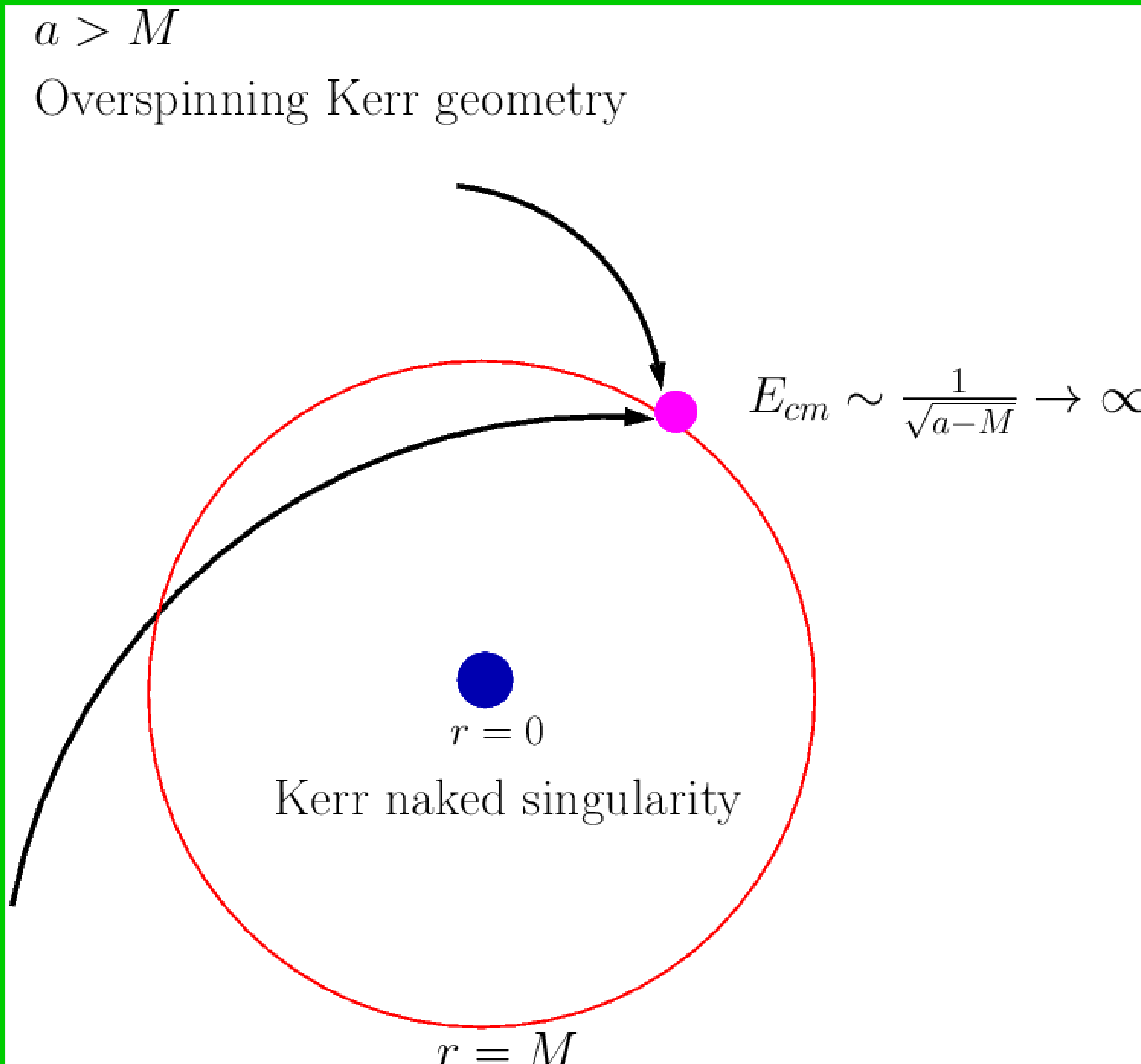
Near-extremal overspinning Kerr spacetime

Patil, Joshi CQG 11, PRD 11

Extremal Kerr Black hole



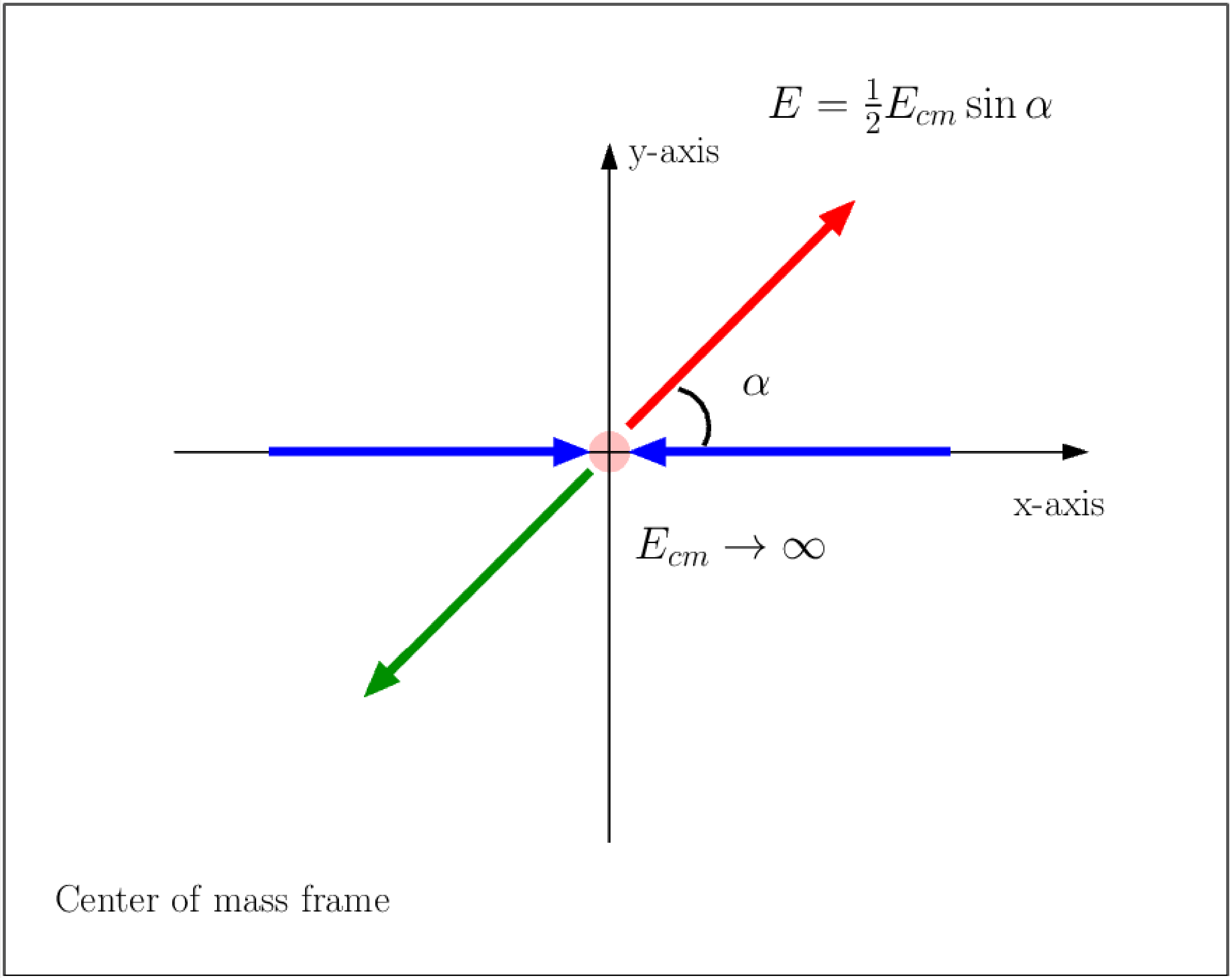
Near-extremal overspinning Kerr geometry



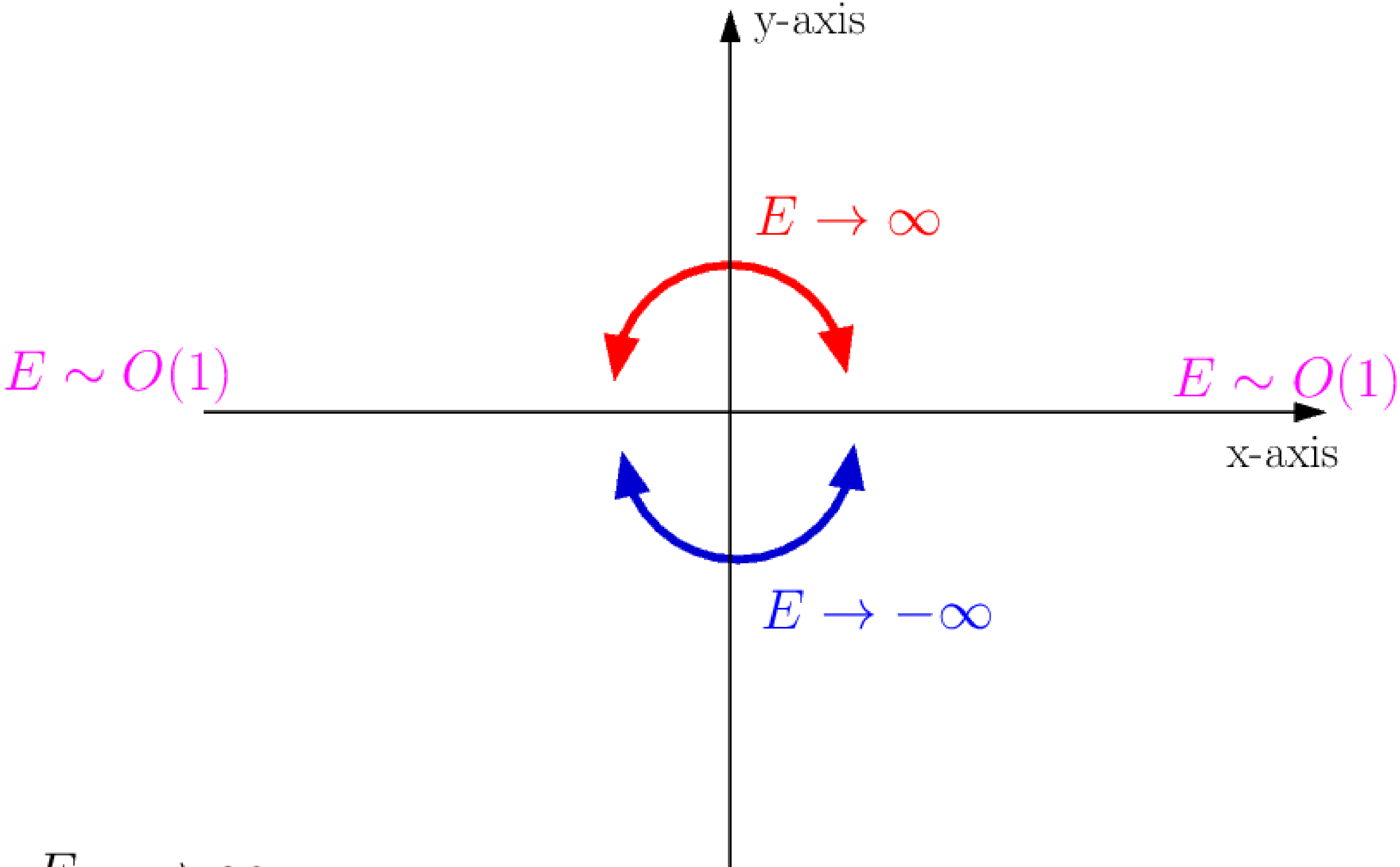
It is possible to have collisions with divergent center of mass energy in the extremal Kerr black hole and in the near-extremal overspinning Kerr spacetime geometry.

It would be possible to produce particles with divergent conserved energy.

It is conveninet to use center of mass frame for further analysis.


$E = \frac{1}{2}E_{cm} \sin\alpha$
y-axis
α
x-axis
$E_{cm} \to \infty$
Center of mass frame

$$E = \frac{1}{2} E_{cm} \sin \alpha$$



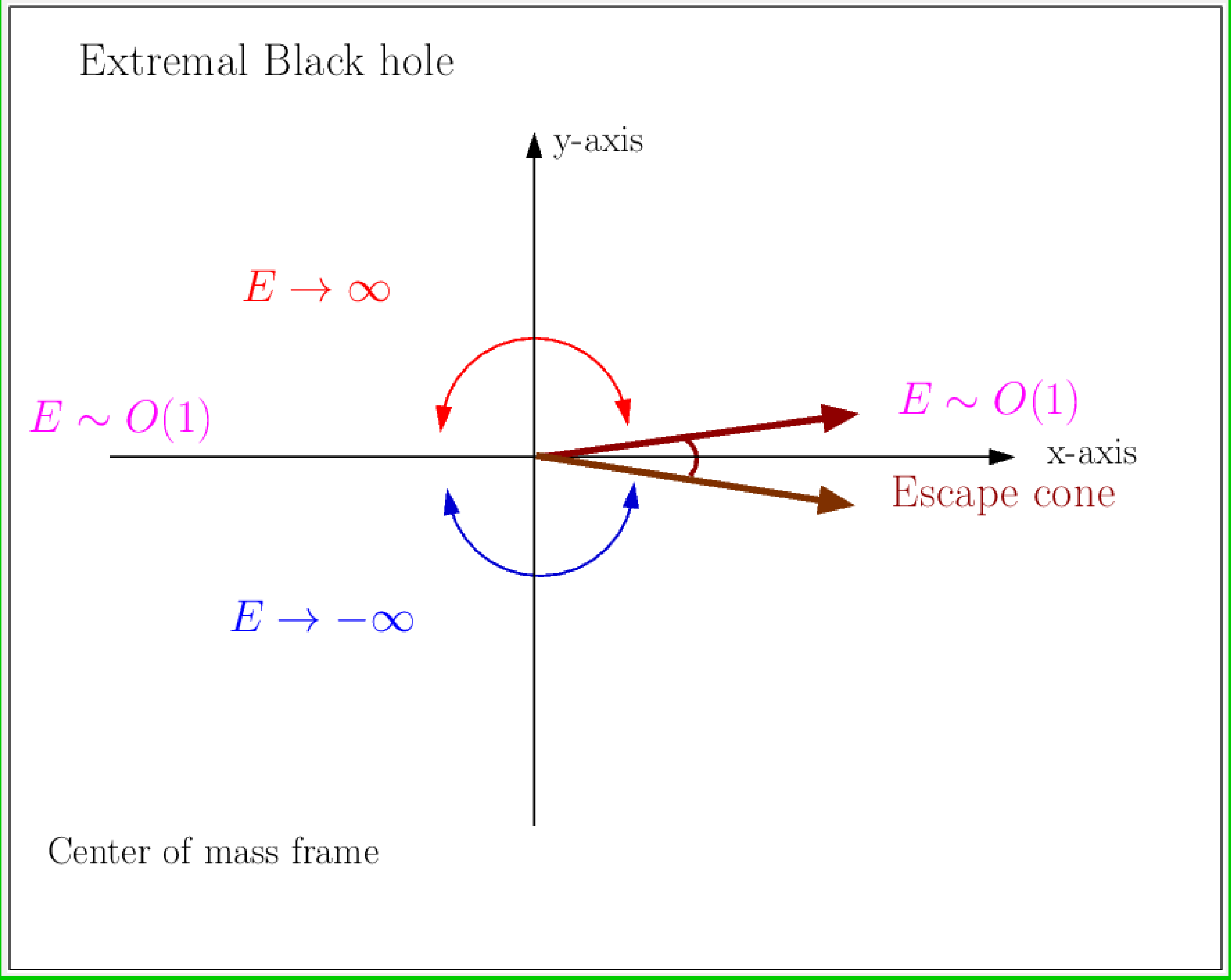
$E_{cm} \to \infty$

Center of mass frame

Can particle with divergent conserved energy escape to infinity ?

By analyzing geodesic motion we identify the escape cone in the center of mass frame.

Extremal Black hole



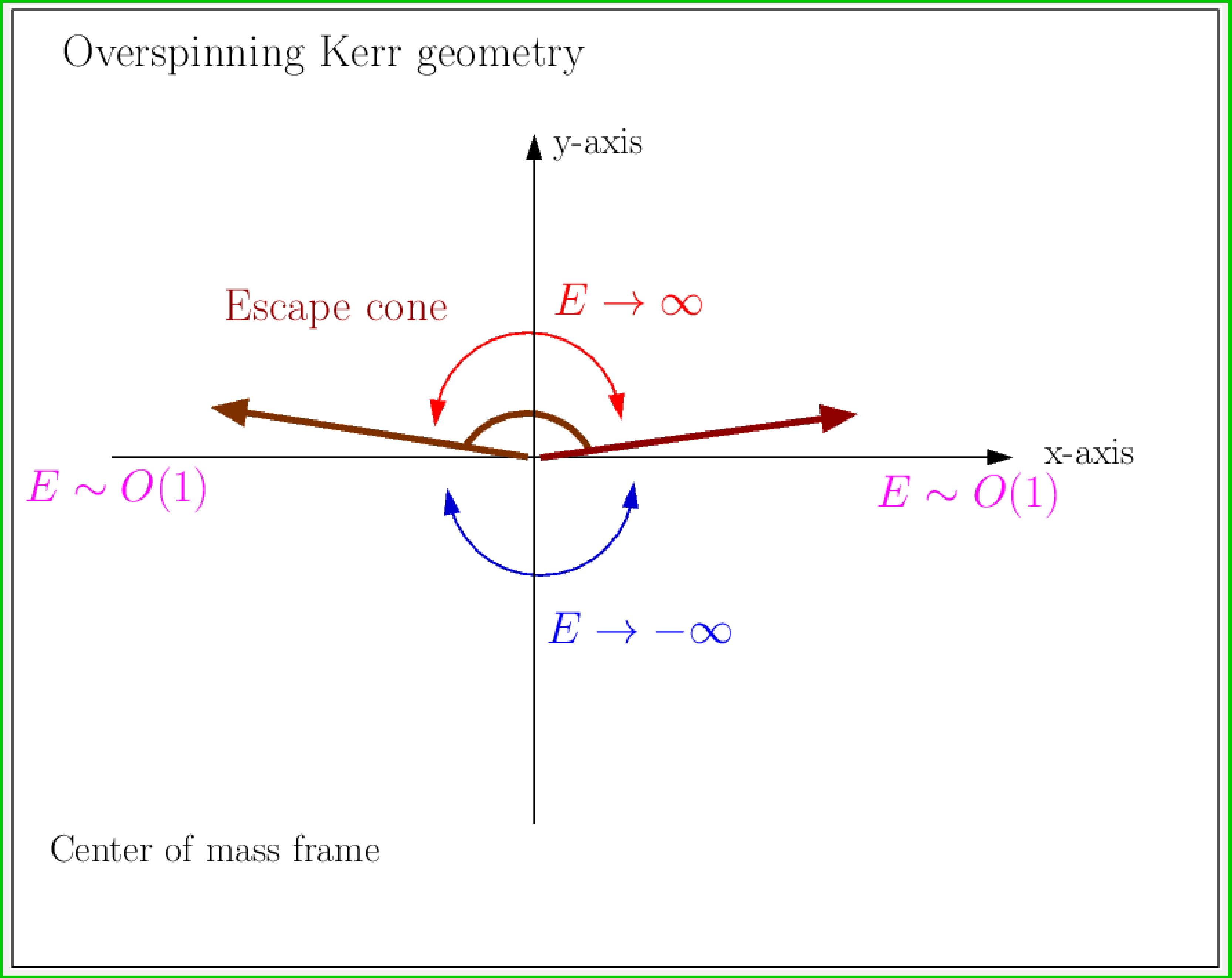
Extremal Black hole

Particles with divergent conserved energy eneter black hole.

Collision takes place near the event horizon. Since the center of mass moves in the radially inwards, particles produced in the collision are strongly beamed towards the black hole.

Particles that escape to infinity have finite conserved energy. Thus black holes cannot serve as the source of ultra-high energy particles.

Near-extremal overspinning Kerr geometry



Near-extremal overspinning Kerr geometry

Particles with divergent conserved energy escape to infinity !!!!!!!

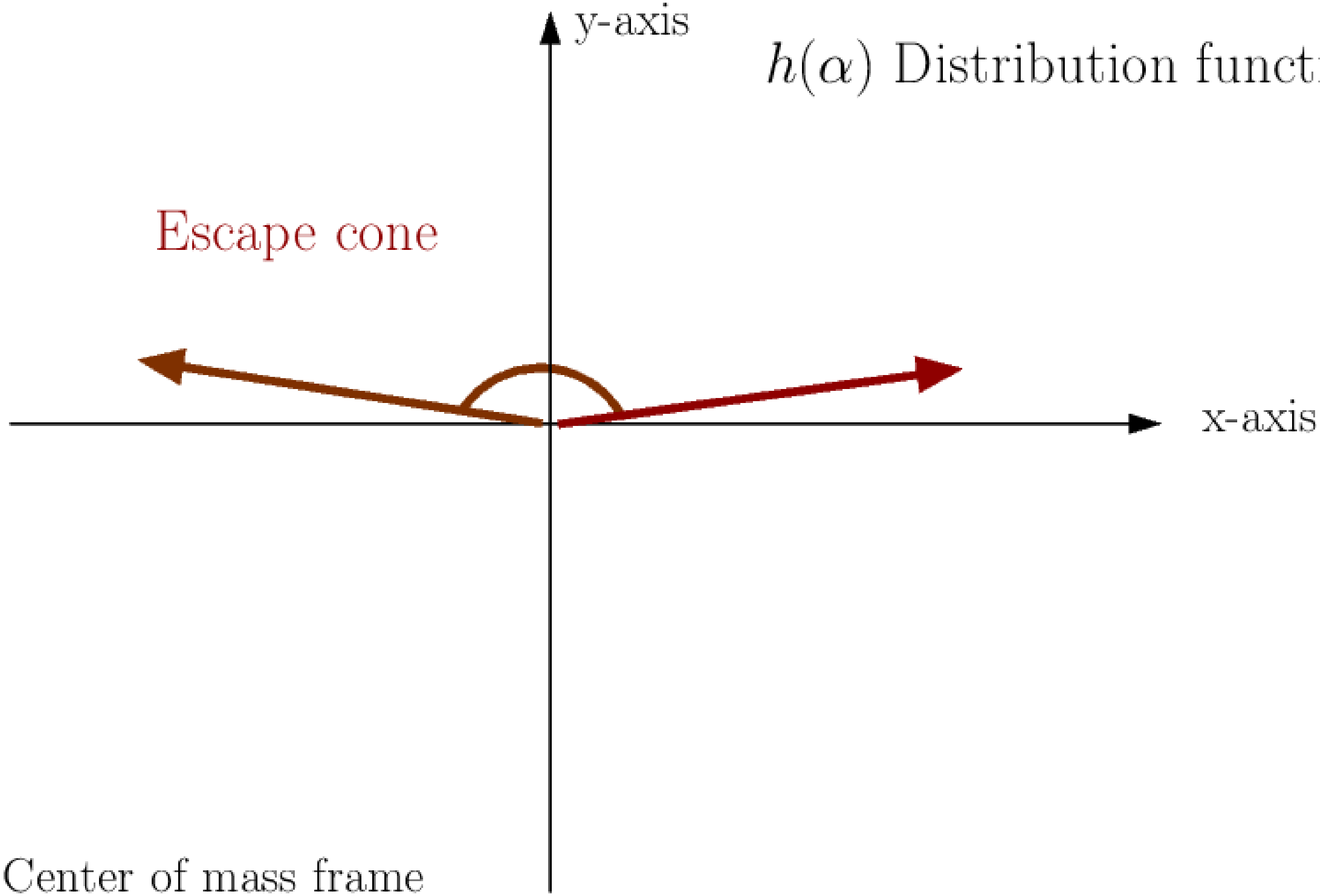
Collision takes place at a location sufficiently away from the singularity. Center of mass can move either in the radially inward or outward direction. Particles produced in the collision can be beamed either inwards or outwards. Particles moving inwards turn back much before they encounter singularity and escape to infinity.

Thus near-extremal over-spinning Kerr geometry can be the source of ultra-high energy particles !!!!!!!

Overspinning Kerr geometry

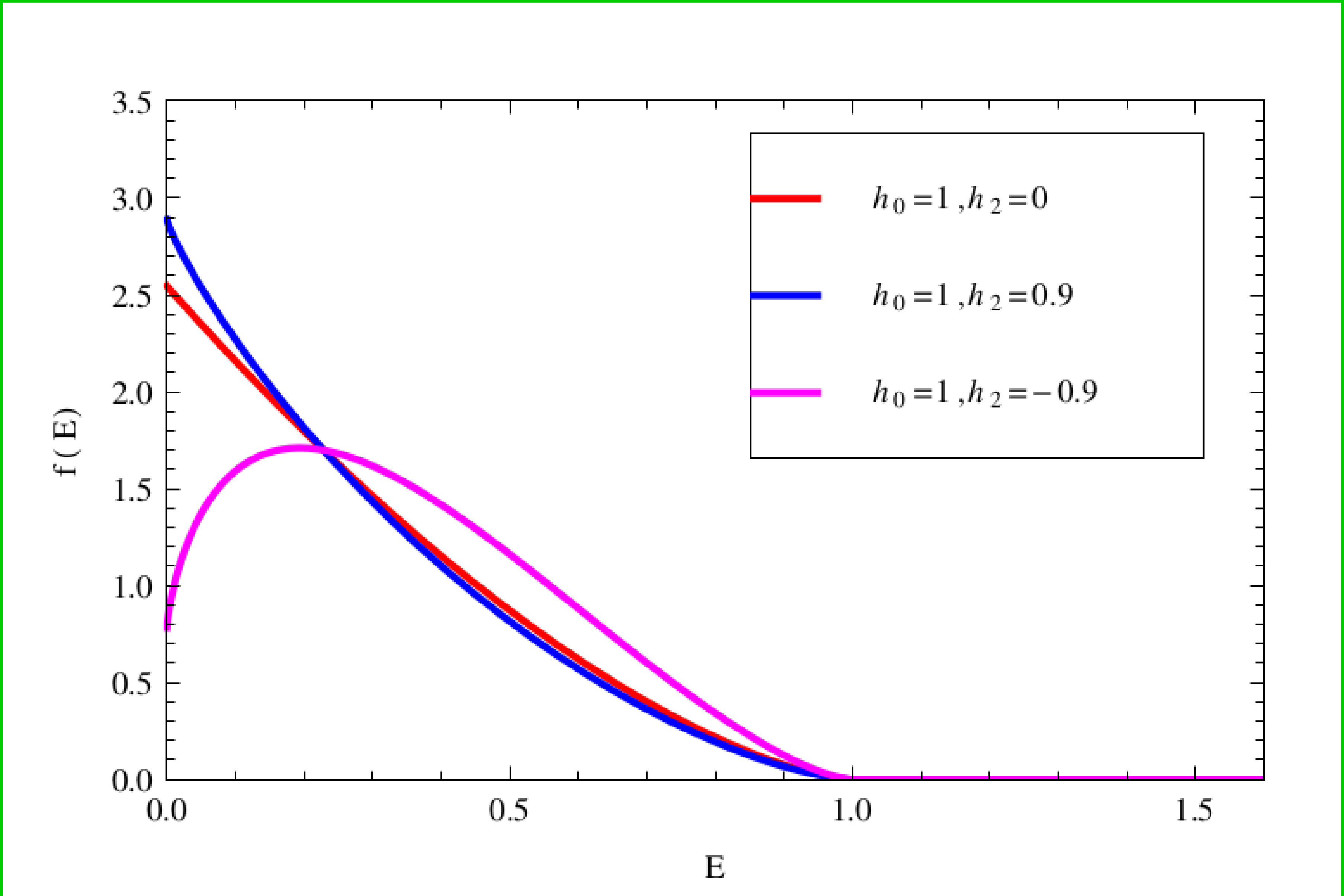
$$E = \frac{1}{2} E_{cm} \sin \alpha$$

$h(\alpha)$ Distribution function



Center of mass frame

Energy distribution function



Cross-section of the underlying particle physics process determines the angular distribution function for the ultra-high energy massless particles produced in collision in the center of mass frame.

Information about the angular distribution function is imprinted on the energy spectrum of the ultra-high energy massless particles.

Thus observation of the spectrum can constrain the particle physics models at the ultra-high energies at which particles collide.

To summarize

It is possible to have collisions with divergent center of mass energy around extremal Kerr black hole and in the near-extremal overspinning Kerr geometry.

Particles with divergent conserved energy are produced in the ultra-high collisions.

Particles with divergent conserved energy enter black hole.

To Summarize

Particles divergent conserved energy produced around near-extremal overspinning Kerr geometry escape to infinity.

Thus overspinning Kerr geometry can serve as the source of ultra-high energy particles.

Energy spectrum of ultra-high energy particles carries an imprint of the cross-section of the underlying particle physics process. Thus it can be a diagnostic of fundamental physics at high energy.

What`s next

Go off the equatorial plane.

Better understanding of the distribution of the colliding particles.

Understand the interaction of the ultra-high energy particles with the surrounding to come up with the more realistic estimation of the spectrum.

Put in the particle physics inputs.

Thank you !!

Collaborators

T. Harada, P. Joshi, K. Nakao. M. Kimura.